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Measurement of Vehicle Particulate Emissions

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A constant volume sampler (CVS) compatible auto exhaust particulate sampling system has been built which samples exhaust isokinetically at constant temperature. This system yields internally consistent results and is capable of frequent and convenient operation.

This paper describes an auto exhaust particulate sampling system developed at Esso Research and Engineering Company. This system is capable of frequent and convenient operation, is compatible with constant volume sampling (CVS) of auto exhaust, and collects particulate matter at constant temperature during the 1972 or 1975 Federal Test Procedure. Compatibility is obtained because the particulate sampler requires only a small portion of the diluted exhaust, the major portion of the sample is available to the CVS system for the measurement of gaseous emissions. Conditions used in the measurement of exhaust particulate conform to those mandated by the Federal Test Procedures for gaseous emissions.

Comprehensive investigations of auto exhaust particulate production have been hampered by the absence of collection and sampling systems that would allow meaningful and reproducible particulate emissions data to be obtained. While several laboratory methods are now being used to collect automotive particulate, they cannot be operated conveniently or frequently, and do not allow simultaneous assessment of gaseous emissions, that is, they are not compatible with the CVS system. The sampling systems used by earlier workers (*1,2*) are similar and are handicapped by similar problems, namely, slow mixing of diluent air and exhaust, settling of particulates in the mixing tunnel, and temperature variations at the particulate collection zone during a run. An accurate mass balance for exhaust particulate includes an accounting of the particulate deposited in the tunnel sampling system. This requires system disassembly, cleaning, and reassembly, which are cumbersome and tedious operations. While useful studies can be made with these systems, they do not lend themselves to the frequent and repetitive particulate emissions testing required to ultimately develop emissions standards and certification procedures.

The system described in this paper is free of the above defects. Mixing is rapid, particulate settling is negligible and disassembly after each run, although convenient, is not required.

System Design

The exhaust particulate samples shown schematically in Figure 1 consists of five major components: (1) a diluent air preparation system, (2) a flow development tunnel, (3) an exhaust injector system, (4) an isokinetic sampling probe, and (5) a particulate measuring device, which in the case shown is a 0.2 μm glass fiber filter.

The overall function of this system is to

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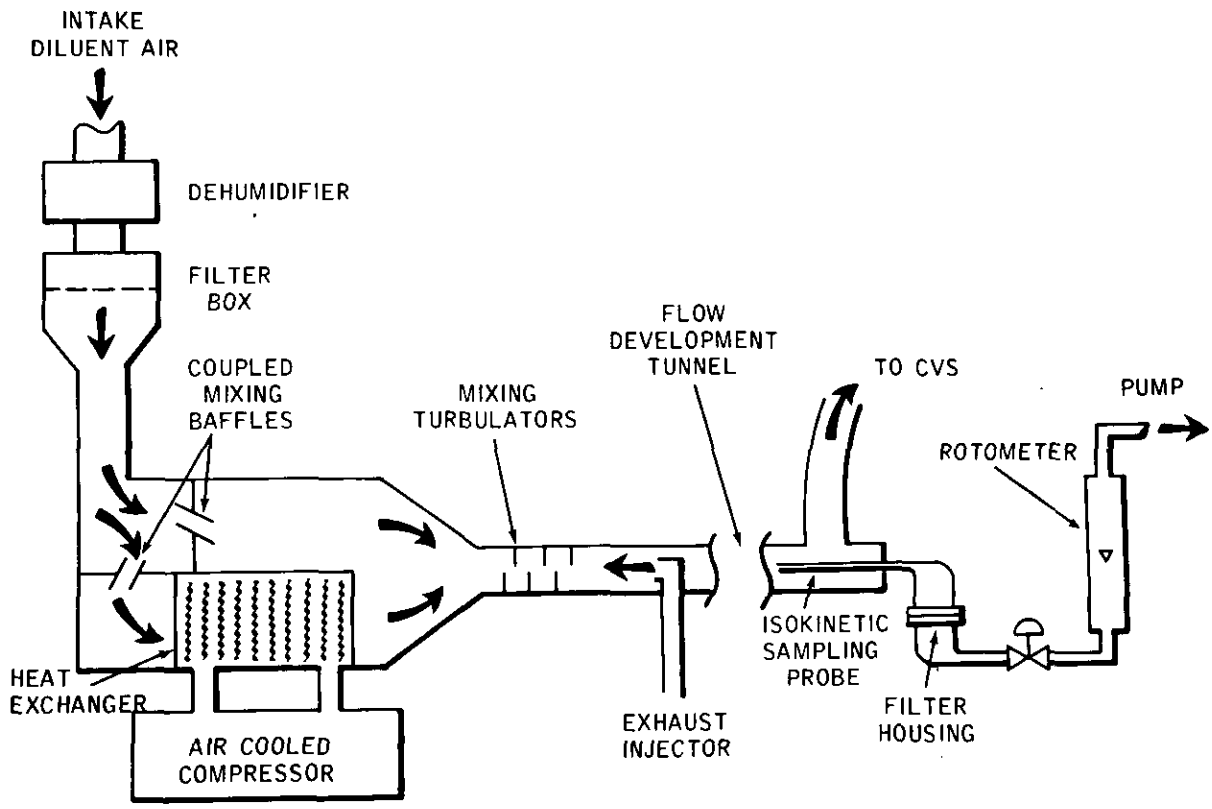

FIGURE 1. Exhaust particulate sampler.

allow the collection of particulate matter from an isokinetically sampled portion of diluted exhaust which has been cooled to 90°F. by dilution with chilled, dehumidified, filtered air. The function of each of the components in accomplishing this objective is described below.

Diluent Air Preparation System

This system consists of a dehumidifier, filter, coupled mixing baffles, a cooling system, and mixing turbulators.

The dehumidifier shown schematically in Figure 2 minimizes the possibility of condensation occurring in the sampling system during a run, and is an integral part of the temperature control system. Diluent air is dried by passage through a filter and a slowly rotating desiccant wheel containing laminated flat and corrugated asbestos, impregnated with a regenerable desiccant, LiCl.

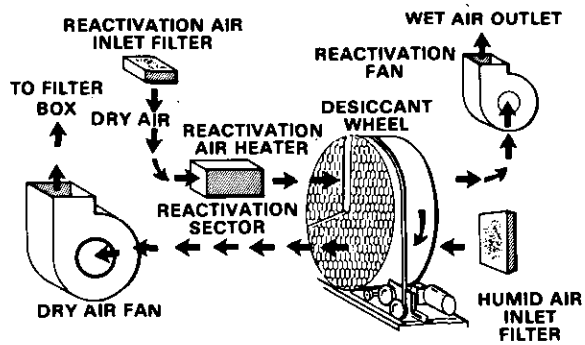

FIGURE 2. Schematic of dehumidification section.

Dehumidification of diluent air and desiccant reactivation are concurrent processes, so that dehumidification can be carried out on a continuous basis. The relative humidity of the dehumidified air is monitored continuously by an electric hydrometer (*3*).

Dehumidified inlet air passes from the dehumidifier to a filter box containing a paper filter, a bed of activated charcoal, and a sec-

ond paper filter. This assembly is the standard filter box assembly for the Scott research constant volume sampler (CVS) unit. The filter assembly removes the particulate matter present in the diluent air and reduces and stabilizes the background hydrocarbon content of the diluent air.

The coupled mixing baffles continuously divide the dehumidified, filtered air into two portions, one which passes through the cooling system, and a second portion which bypasses the cooling system. The position of the mixing baffles is controlled by a rapid response, deviation-type controller operating on an input signal from a thermocouple in the filter housing. The system is designed to maintain 90°F at the filter housing during the 1972 or 1975 Federal Test Procedures.

The cooling system is an air cooled condensing evaporator which has a cooling capacity of 30,000 BTU/hr.

The mixing turbulators insure that chilled air is thoroughly mixed with the portion of air by-passing the cooling system before the stream is used to dilute the vehicle exhaust. The turbulators consist of six semicircular perforated plates attached to a ½ in. diameter wall tube at their centers, arranged in a helical series sequence along the tunnel axis. This arrangement allows both longitudinal and latitudinal mixing.

Maximum flow through the diluent air preparation system is determined by the cooling capacity of the chiller. Presently, this limitation is 450 CFM.

Flow Development Tunnel

The exhaust and diluent air are mixed and a uniform velocity profile is developed in the flow development tunnel. The flow development tunnel is a 7.5-ft long section of 4 in. diameter Schedule 5 stainless steel pipe. Neither the length nor the diameter of the flow development tunnel have been optimized, but as will be shown in another section, a dilution tunnel of these dimensions is satisfactory for this purpose.

The Exhaust Injection System

The raw exhaust is mixed with the diluent air normally used in the CVS in such a way as to completely mix the two in as short a time interval as possible. Three methods of injecting exhaust into diluent air have been tested: cocurrent flow, perpendicular flow, and countercurrent flow. A description of the experiments leading to the choice of this technique is presented in a subsequent section. Figure 3 shows a schematic of the exhaust injector in the countercurrent position.

Isokinetic Probe

Isokinetic sampling is required to insure that the particulate sampled is representative of the particlulate in the main stream; that is, the particlulate concentration and size distribution in the probe sample should correspond to that of the main stream. The probes are so designed that the sample stream is divided into two parts with a volume ratio equal to the ratio of the cross-sectional areas of the openings of the sample probes and the tunnel cross-sectional area:

$$\frac{\text{Area(probe)}}{\text{Area(tunnel)}} = \frac{\text{Flow Rate in SCFM(probe)}}{\text{Flow Rate in SCFM(tunnel)}}$$

Another problem to be considered in probe design is minimizing sample deposition in the probes. When suspended particulate matter leaves the tunnel and enters the sampling probe, it is leaving a low surface to volume region and entering a high surface to volume region. Relative sample losses by impaction should be greater in the probe than in the

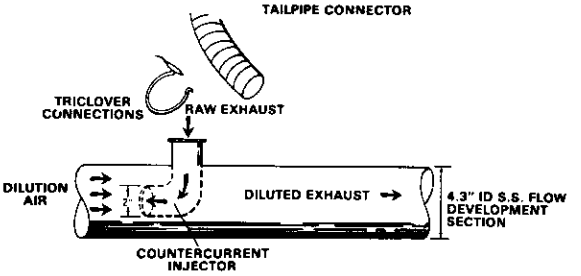

FIGURE 3. Countercurrent exhaust injection system.

tunnel. Therefore, the probe should be as short and direct as possible to minimize the residence time of the particulate matter in the probe. The filter housing connected to the probe is flared out as soon as physically possible to minimize the surface to volume ratio of the housing and thereby reduce sampling losses by impaction in this portion of the sampling system.

Particulate Collecting Stage

At present, particulates are collected by filtering the sample through preweighed filters. In principle, other particulate collectors such as impactors and other devices, could be utilized with the particulate sampling system. In this paper, total particulates are determined gravimetrically by using Gelman Type E glass fiber filters which have an effective porosity of 0.2 μm.

A properly functioning exhaust particulate sampling system should do the following: mix exhaust and diluent air rapidly; allow development of a uniform velocity profile in the flow development tunnel; minimize sampling losses in the tunnel; give equivalent emission rates with parallel filters; maintain constant temperature at the particulate collecting stage.

A discussion of the calculations and experiments carried out to determine if the above criteria are met follows.

Rapid Mixing of Exhaust and Diluent Air

Three methods of injecting exhaust into diluent air were tested: cocurrent flow, perpendicular flow, and countercurrent flow. In each case, the exhaust was injected through a 2-in. O.D. $\times$ 0.035 in. wall stainless steel tube into the flow development tunnel. The efficiency of the three injection methods was tested by measuring hydrocarbon concentrations in the diluted exhaust at a point approximately 7.5 ft downstream of the injection point. Hydrocarbons were chosen as the tracer because they are easier to measure than particulates. If the gaseous components of the exhaust are not evenly distributed over the flow cross section, there is no reason to think that the particulates will be well distributed. The ultimate test of uniformity of particulate distribution in the tunnel is the consistent attainment of equivalent particulate emission rates with parallel filters. Experimental data substantiating this uniformity is discussed in the system performance section of this paper.

The results obtained with cocurrent injection were very poor. Hydrocarbon was found concentrated in the quadrant in which it was injected. Perpendicular injection gave somewhat better results, but was poorer than countercurrent injection, which gave uniform distribution across the pipe. Table 1 contains a summary of the hydrocarbon tracer results for perpendicular and countercurrent injection.

Table 1. Hydrocarbon tracer studies.

Probe location	Hydrocarbon concentration, ppm	
	Perpendicular injection	Countercurrent injection
Center line	35	44
Bottom +1/2 in.	52	44
Above bottom	48	44
+1 in.	44	43
+1.5 in.	40	44
+2 in.	37	43
+2.5 in.	34	43
+3 in.	32	43
Bottom	52	44

Table 2. Effect of Reynolds number on velocity profile.

N_{Re}	N	$\bar{u}/U$
23,000	6.6	0.807
110,000	7.0	0.816
500,000	8.0	0.837

Development of Uniform Flow in Flow Development Tunnel

To insure that samples taken at any point in the tunnel cross section will contain the

same amount of particulate material, a uniform radial distribution of particulate material in the tunnel must be obtained. It is well known that the higher the Reynolds Number of turbulent flow, the flatter the velocity profile (*4*). However, over the range of interest for this system, the effect of this flattening of the velocity profile is negligible. Consider the system as having a flow of 450 SCFM of air at 90°F through a 4.33 in. diameter pipe.

$$N_{Re} = \frac{DU\rho}{\mu} \qquad (1)$$

where N_{Re} is Reynolds Number, D is pipe diameter = 4.34 in. = 0.361 ft; U is average fluid velocity = $4(450)/\pi D^2 = 4395$ ft/min = 2.64×10^5 ft/hr; ρ is density = 0.071 lb/ft^3, μ is fluid viscosity = 0.186 cP = 0.045 lb/ft-hr. Then

$$N_{Re} = \frac{(0.361)(2.64 \times 10^5)(0.71)}{0.045} = 150{,}000$$

Equation (1) shows that the Reynolds Number varies inversely with diameter for constant volumetric flow. Therefore, decreasing pipe diameter to 1 in. would increase N_{Re} to 615,000 while increasing pipe diameter to 16 in. would decrease N_{Re} to 40,000.

One measure of the flatness of the velocity profile is the ratio of the mean gas velocity to the maximum gas velocity. It has been shown experimentally that, for turbulent flow in smooth pipes (*4*),

$$\frac{u}{U} = \left(\frac{Y}{R}\right)^{1/N} \qquad (2)$$

where u is point velocity, U is maximum velocity at center, Y is distance from the wall, R is pipe radius, and N is a constant depending on Reynolds Number.

Schlicting (*4*) shows that the average velocity u is,

$$u = \frac{2N^2}{(N+1)(2N+1)} \qquad (3)$$

Table 2 shows that the effect of changing pipe diameter over a large range would be negligible.

Another important factor in choosing the diameter of the flow development tunnel is its effect on the length of the tunnel and the diameter of the probes. As a general rule, ten pipe diameters are usually sufficient to develop a fully turbulent velocity profile. The larger the diameter, the longer the tunnel required and the longer the residence time in the flow development section. Longer residence time leads to higher particulate settling and greater inaccuracy in the measurement. Therefore, the tunnel diameter should be minimized. However, as tunnel diameter decreases, the pressure drop through the tunnel increases and the size of the probes needed for isokinetic sampling decreases. The problems caused by high pressure drop are obvious. Smaller diameter probes should be avoided since they provide higher surface to volume ratios and result in more loss of particulate by impaction. The 4.3 in. diameter pipe in use offers a reasonable compromise between these various factors.

Tunnel Sampling Losses

Particulate deposition in the flow development section was measured by introducing an artificially produced mono-disperse (3.5 μm diameter) methylene blue aerosol into the exhaust injector in the same manner as for auto exhaust. The system was disassembled after the run, the tunnel surface washed with methanol and the washings analyzed spectrophotometrically. Analysis showed that tunnel losses are small, amounting to less than 1% of the total aerosol introduced. No dye was detected in the tunnel section housing the exhaust injector. About 0.1% of the aerosol was deposited in the tunnel midsection and about 0.3% was deposited in the tunnel section housing the probes.

Equivalent Emission Rates with Parallel Filters

Since only a small fraction of the diluted exhaust is sampled for the particulate analysis, at least two parallel probes coupled to the appropriate filters are needed to serve as internal checks on the sampling system. One method of determining whether proper sampling is achieved relies on the ratio of the weight of particulate collected (W_A) by filter A, and the volume flow rate (F_A) through probe A. This ratio should equal the corresponding ratio of these parameters for filter B and probe B, that is:

$$\frac{W_A}{F_A} = \frac{W_B}{F_B} = \frac{W_C}{F_C} = \ldots \tag{4}$$

The particulate emission rates in grams per mile (g/mi) should be the same for all filters in a given run since

$$\frac{g}{mi} = \frac{W_A}{F_A}\left(\frac{F_p}{M}\right) = \frac{W_B}{F_B}\left(\frac{F_p}{M}\right) = \ldots \tag{5}$$

where F_p is the volume flow rate through the tunnel and M the mileage accumulated on the particular test procedure.

Excellent agreement between parallel filters has been obtained using this sampling system with conventional and catalyst equipped vehicles operating on a variety of unleaded fuels under cyclic and state test conditions. The agreement as shown in Figure 4, obtained over a wide-range of particulate emission rates by various test vehicles under a variety of test conditions, indicates that the system is functioning properly.

Filter housings were so designed that regardless of probe (volume) sampling rates, the filter face velocities (probe volume sampling rate divided by the filter area) were closely matched, thereby eliminating filter face velocity as a parameter that could influence agreement between parallel filters.

A short series of tests was made involving use of two parallel probes sampling at different rates (3.3 and 10 CFM) but with closely matched filter face velocities (67.3

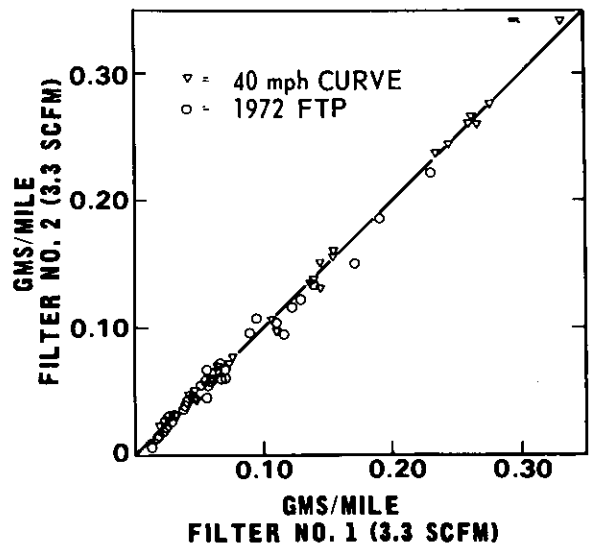

FIGURE 4. Filter correspondence. Ratio of g/mile for filter 1 vs. g/mile for filter 2 obtained with conventional vehicles and vehicles equipped with catalytic converters operating on various (unleaded) fuels under cyclic and steady-state conditions: (△) 40 mph cruise; (O) 1972 FTP.

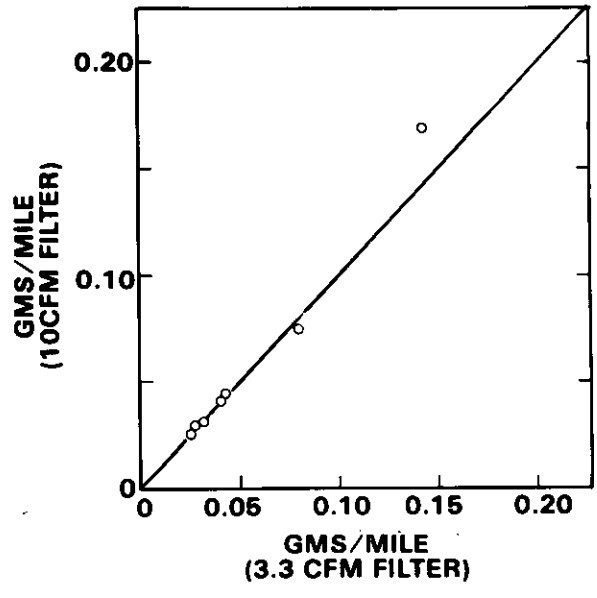

FIGURE 5. Filter correspondence. Ratio of g/mile for 10 CFM and 3.3 CFM filters, for standard production vehicle operating with various unleaded fuels; 1972 Federal Test Procedure. F

and 65.8 ft/min, respectively for the 3.3 and 10 CFM filters). Figure 5 shows the agreement between these filter pairs.

Our early experience in developing the particulate sampling system showed that probe surface to volume ratios and length were the key parameters affecting parallel filter correspondence. Sampled particulate matter in leaving the flow development tunnel and entering the probes is going from a low to a high surface to volume region. This means that the probability of sample losses in the probe relative to the tunnel can be considerably higher. The absolute quantity of particulate entering the probe is but a small fraction of the total particulate in the tunnel. The ratio of particulate deposited in the probe to the quantity of particulate that entered the probe, can be considerably greater than the corresponding ratio for particulate in the tunnel.

When sample losses in the probes are appreciable, filter correspondence would be expected to be poor, and accordingly no true assessment of particulate emission rates can be made under these circumstances. Our experience has shown that by using short, direct probes, and minimizing probe surface to volume ratio, discordant results between parallel filters were eliminated.

Figure 6 shows the type of correspondence obtained when portions of the particulate being sampled were deposited in the longer sampling probes. Thus, it is not sufficient to thoroughly mix exhaust with diluent air and obtain a uniform velocity profile, deposition of sampled particulate matter prior to collection must be prevented.

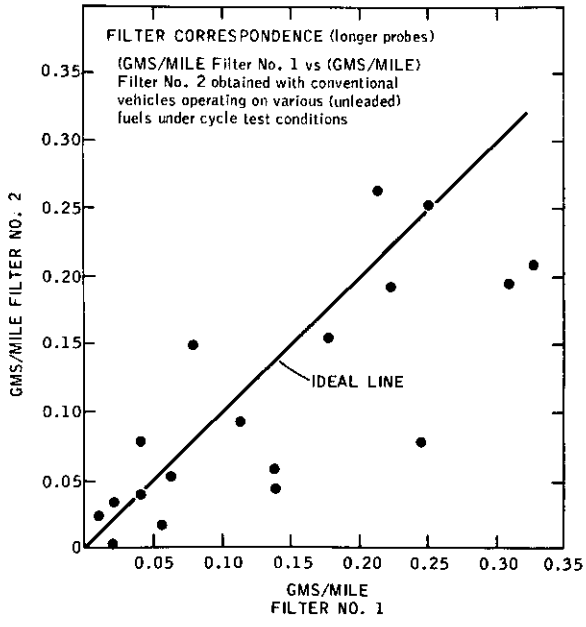

FIGURE 6. Filter correspondence with longer probes. Ratio of g/mile for filter 1 vs. filter 2 obtained with conventional vehicles operating on various (unleaded) fuels under cycle test conditions.

Temperature Maintenance at the Particulate Collection Stage

Filter temperatures can be maintained during the LA–4 cycle when testing a catalyst equipped vehicle. The CVS unit is operated at 450 CFM using chilled, dehumidified air, and a 4-ft long finned tube between the tailpipe and exhaust injector. The relative humidity of the diluted exhaust remains below 100% during the test cycle. Figure 7

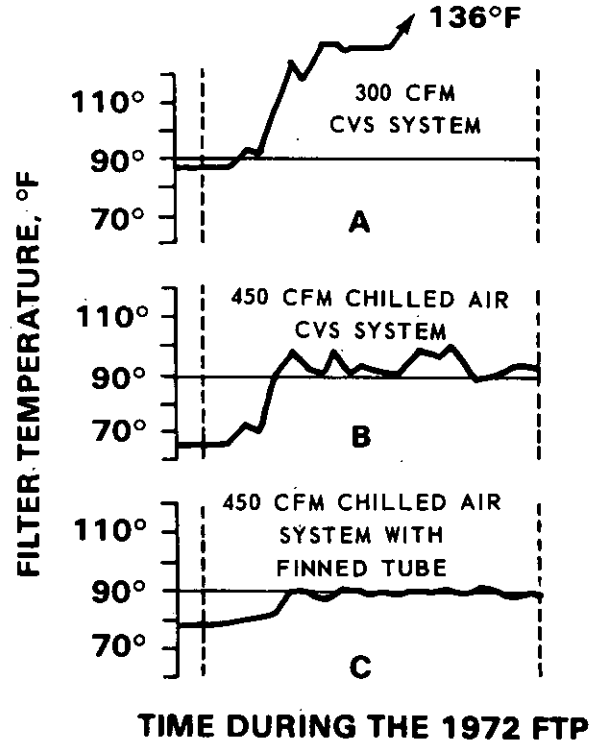

FIGURE 7. Temperature control system performance for catalyst-equipped car.

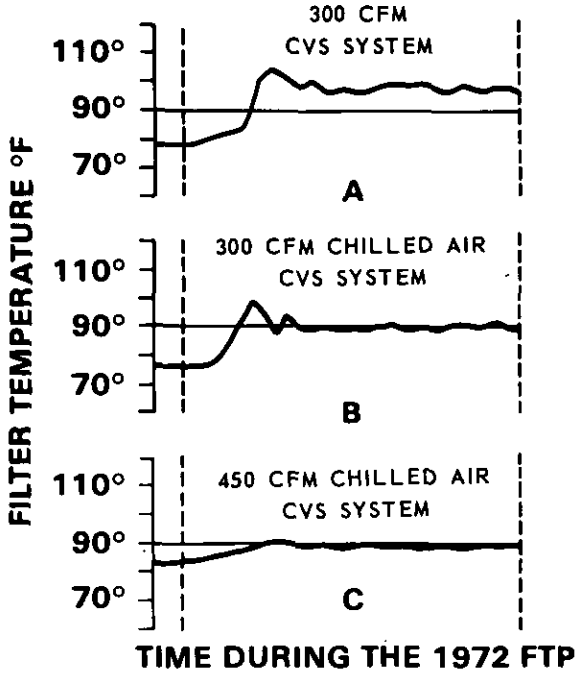

FIGURE 8. Temperature control system performance for 1970 Chevrolet.

shows the temperature behavior at the filter housing during runs made under those cooling conditions, with a 350 CID V–8 vehicle equipped with two monolithic noble metal oxidation catalysts. In the first case, Figure 7*A*, where a 300 SCFM total flow was used with no cooling, the filter temperature reached 136°F. Figure 7*B* shows the case in which the total flow of 450 SCFM was used with chilling. Filter temperature was maintained between 95° and 100°F. Insertion of a 4-ft finned tube (Fig. 7*C*) allowed control to 90°F. The system is designed to prevent temperature excursions above 90°F.

Filter temperature control is more easily attained operating a conventional, noncatalyst vehicle over the Federal Test Procedure. Figure 8*A* shows that in the absence of temperature control, at 300 CFM, the filter temperature ranges from about 100 to 105°F, after the first acceleration. At 300 CFM, the chilled air system provides satisfactory temperature control except during the maximum acceleration portion of the cycle Figure 8*B*. At 450 CFM (Fig. 8*C*) complete temperature control is attained with the chilled air system.

Control of the filter temperature could not be accomplished without the dehumidifier because water condensation and freezing on the heat exchanger would decrease its efficiency and possibly render it inoperative. Dehumidification also allows lower air-exhaust dilution ratios to be attained without dropping below the dew point of the resultant mixture.

Figure 9 depicts the dependence of the mixture dew point–air dilution relationship on the relative humidity of the diluent air.

Figure 10 shows a typical trace of the relative humidity of the diluted exhaust in the vicinity of the sampling probes during FTP operation with a catalyst equipped vehicle. This trace is obtained by withdrawing a sample just above the sampling probes and filtering it prior to monitoring the humidity. Filtration is necessary in order to protect the humidity sensor.

It is evident that the relative humidity in the region of the probe closely parallels the changes in the cycle driving patterns. At no point in the driving cycle does the relative humidity at the probes reach the saturation level at 90°F. As the relative humidity is lower upstream, condensation in the tunnel upstream of the probe does not occur.

Figure 11 is a typical relative humidity–time trace for a 40 mph steady-state cruise experiment. The relative humidity surges to about 25% on start up and slowly decreases with running time. After 20 min at 40 mph, the filter temperature slowly rises above 90°F. The exhaust particulate sampler was designed to maintain constant temperature over the Federal Test Procedure; additional system modification should allow constant filter temperatures to be maintained for longer time periods under cruise conditions, and at higher cruise speeds.

This method of temperature control avoids the undesirable phenomena associated with other possible methods of temperature control, because it conditions the diluent air, not the diluted exhaust. For example, temperature control could be achieved by cooling the sampling probes, but this would result in

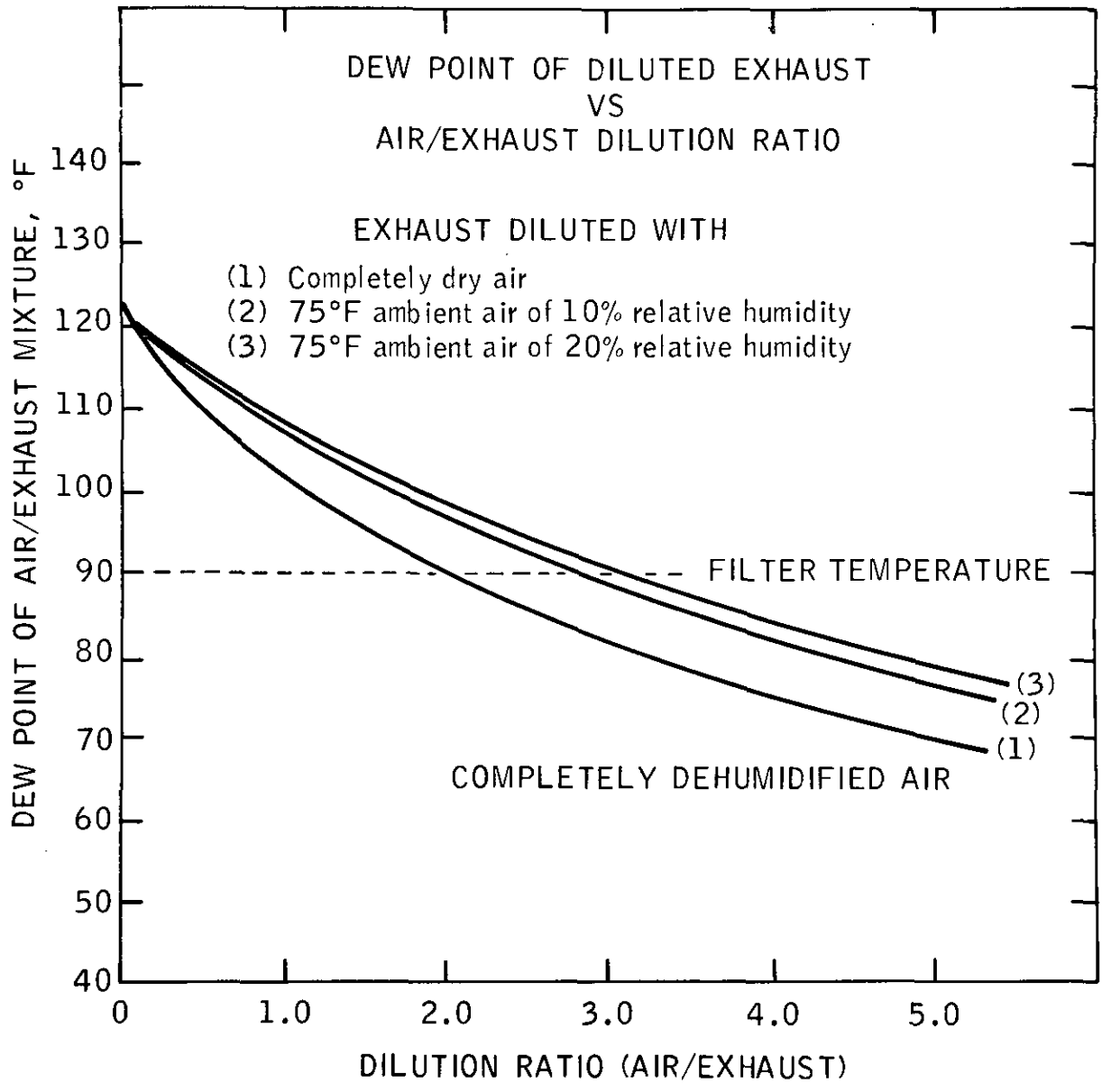

FIGURE 9. Dew point of diluted exhaust vs. air/exhaust dilution ratio for exhaust diluted with (*1*) completely dry air, (*2*) 75°F air of 10% RH; (*3*) 75°F air of 20% RH.

sample losses due to thermophoretic deposition, and condensation. Temperature control could also be achieved by using much higher dilution rates. This decreases the accuracy with which gaseous emissions can be measured. Higher dilution ratios means that longer tunnels are required to insure mixing, which means longer tunnel residence times, resulting in higher sample losses in the tunnel.

Capabilities of the Exhaust Particulate Sampling System

The sampling system discussed in this paper represents a considerable advance over earlier vehicular exhaust particulate sampling systems because of a number of mutually interdependent features. Since the dilution air and vehicle exhaust are mixed

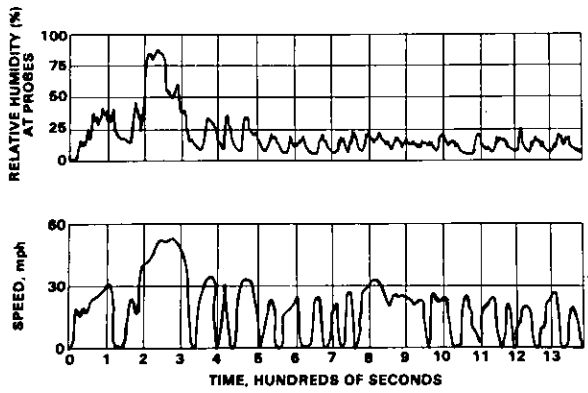

FIGURE 10. Relative humidity of exhaust dilution air mixture in vicinity of sampling probes during the 1972 Federal Test, driving cycle.

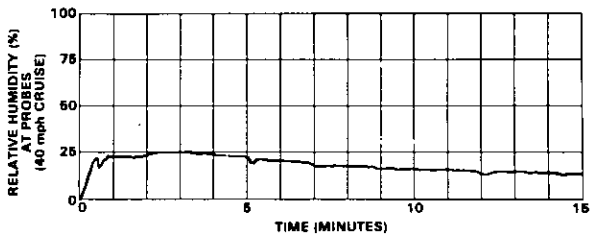

FIGURE 11. Relative humidity of exhaust dilution air mixture in vicinity of sampling probes during 40 mph cruise conditions.

efficiently, smaller sampling tunnels can be used. Sample losses by settling are low in smaller tunnels because of reduced tunnel residence time. This, in turn, means that tunnel disassembly is not required to achieve a particulate material balance, which allows more frequent operation. Finally, a standard condition for collecting particulate matter during urban driving cycles is provided by the temperature control system.

Taken together, the above features and capabilities mean that the exhaust particulate sampling system is both a useful tool for research purposes, and a candidate for use in possible vehicular particulate certification tests. As a research tool, it has proven to be useful for studying vehicular particulate emission rates and particulate composition as a function of such parameters as fuel composition, and vehicle operating conditions. This system has been particularly useful in determining differences in particulate emission patterns between conventional vehicles and vehicles equipped with advanced emission control devices. Some of the results of these studies have been presented at the February 25–March 1, 1974 SAE Congress (*5*).

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